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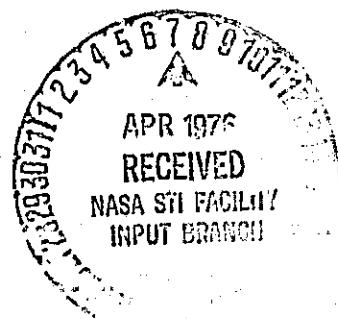
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The Triggering and Subsequent Development of a Solar Flare

Prepared by J. A. VORPAHL
Space Physics Laboratory

31 October 1975



Prepared for NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama 35812

Contract No. NAS8-29602



Laboratory Operations
THE AEROSPACE CORPORATION

(NASA-CF-144228) THE TRIGGERING AND
SUBSEQUENT DEVELOPMENT OF A SOLAR FLARE
(Aerospace Corp., El Segundo, Calif.) 27 p
HC \$4.00

N76-21109

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THE AEROSPACE CORPORATION
El Segundo, California

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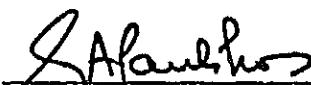
THE TRIGGERING AND SUBSEQUENT DEVELOPMENT
OF A SOLAR FLARE

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Acknowledgments

I am indebted to Dr. Gary Chapman and Ms. Joanna Frawley for playing an integral part in reducing the magnetic field data. Mr. John Castelli at Sagamore Hill provided the microwave data. Helpful discussions were held with Drs. J. Underwood, D. McKenzie, D. Wentzel and N. Krall. I wish to thank all the NASA personnel who made this work possible, in particular the Skylab Astronauts and Mr. J. Milligan, the S-056 Principal Investigator for most of the duration of the project. This work was performed under NASA Contract NAS8-29602.

ABSTRACT

High temporal and spatial resolution solar x-ray pictures of a flare at 1827 UT on 5 September 1973 were taken with the S-056 Aerospace Corporation/Marshall Space Flight Center telescope on the Apollo Telescope Mount. Photographs taken at 9 sec intervals allow detailed information to be obtained about the site of the energy release, as well as about the evolution of the flare itself. Observations suggest that the flare occurred in an entire arcade of loops rather than in any single loop. Sequential brightening of different x-ray features indicates that some excitation moved perpendicular to the magnetic field of the arcade at velocities of 180-280 km/sec. The most intense x-ray features were located in places where the magnetic field composing the arcade had a small radius of curvature with horizontal field gradients higher than the surrounding region and where the axis of the arcade changed direction. We feel that the arcade geometry strongly influenced the propagation of the triggering disturbance, as well as the storage and site of the subsequent deposition of energy. A magnetosonic wave is suggested as the propagating mechanism triggering instabilities that may have existed in the preflare structure. This event demonstrates that all energy emitted during a flare need not be released immediately nor in the same location, thereby eliminating some problems encountered in many flare theories. Conditions for energy release are discussed.

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1. INTRODUCTION

Ellison (1949) defined a flare as a "sudden, short lived increase in monochromatic radiation." Subsequently, however, a wide variety of auxiliary emissions have been observed concurrent with Ellison's "flare" and now the whole group of phenomena are typically referred to as the "flare event". Information about the spatial characteristics of flares was initially obtained through observations made in the chromospheric line of H α (cf., references in Svestka, 1969). In the last years, however, there has been a tendency to think of the H α flare as a secondary product of a coronal instability (Svestka, 1973) and to place the origin of the flare phenomenon above the chromosphere, in the transition layer or the corona. With that in mind, great efforts have been expended to examine flare emissions characteristic of the solar corona in order to learn more about the triggering mechanism itself. For example, soft x-ray images of a flare have been made with rockets (cf., Vaiana, et al., 1968; Vaiana and Giacconi, 1969) and satellites (Neupert, et al., 1974; Beigman, et al., 1969). More recently, as a result of Skylab, thousands of high resolution solar images exist at soft x-ray wavelengths and are presently being examined in the hope of obtaining new information about flares (Vorpahl, et al., 1974, 1975; Kahler, et al., 1975).

A previous paper (Vorpahl, et al., 1975) discussed the general characteristics of 132 soft x-ray flares observed with The Aerospace Corporation/Marshall Space Flight Center S-056 telescope. In this paper we examine one flare, concentrating on details in the x-ray core. The core is defined to be the compact, well-defined region constituting the major source of flare x-radiation (Vorpahl, et al., 1975). High time resolution x-ray pictures taken at 9 sec intervals

allow detailed information to be obtained about the site of the energy release, as well as about the evolution of the flare itself. The intimate connection between specific x-ray features and magnetic field line structures calculated from high resolution Aerospace Corporation magnetograms, obtained at the San Fernando Observatory, is discussed.

2. EXPERIMENT

The S-056 x-ray telescope was one of a cluster of solar instruments carried on the Skylab space station, in operation from May 1973 to February 1974. A detailed description of the instrument has been given elsewhere (Underwood, et al., 1975). In summary, solar images were recorded on film carried in a cassette in roll form. Five filters of thin metal foils, giving the instrument sensitivity in the 6-47 Å range, could be inserted into the optical path and thus provide some spectral discrimination. The instrument could be operated in any one of a number of modes, chosen by the crew member on the basis of current solar activity. The range of exposures possible with any particular filter was 1.25 secs to 40 minutes or more. The crew members were requested to start the S-056 experiment if there were the slightest reason to believe that a flare or transient event might occur. Because of this policy, we obtained observations during the rise of 121 of a total of 132 x-ray flares, with the actual starts observed in 40 cases. One of these well observed flares, occurring at 1827 UT on 5 September 1973, is discussed in this paper.

3. OBSERVATIONAL RESULTS

McMath 510 (Boulder #212) appearing on the east limb on 30 August 1973, was a prolific producer of flares throughout most of its disc passage. Most flares observed in the region during the first few days of September started

in some follower polarity that surrounded the leader spot. This encirclement of opposite polarity had developed by 3 September and remained throughout the 6th. This same time corresponded to the period when the most flares were observed in McMath 510 --- a maximum of 14 events was reported on 4 September alone.

In addition to being inherently interesting, McMath 510 also interacted with other sunspot groups. A transequatorial connection visible in soft x-rays (Vorpahl, et al., 1974), existed with McMath 512 in the southern hemisphere. Sympathetic flare activity between these two regions and between McMath 510 and another southern group, McMath 507, was suggested by the fact that H α flares often overlapped in time and by the fact that simultaneous radio bursts spatially located between the pairs of active regions were typically observed on Culgoora's heliograms (Vorpahl and Stewart, 1975). The x-ray event discussed here was followed by a tremendous H α surge that transited the equator and then bifurcated, with part of the outflow going toward McMath 512 and part towards McMath 507. A long-lived type II radio burst was observed at the time of the H α surge. However, in this paper, we concentrate primarily on the soft x-ray characteristics and their implications regarding the original energy release and the general evolution of the flare event.

Figure 1 consists of x-ray pictures taken with filter 1 (1/2 mil Al; 8-16 \AA), filter 2 (1/4 mil Al; 8-22 \AA) and filter 3 (1/10 mil Ti; 6-14 \AA , 27-47 \AA) prior to and during the start of the event on 5 September 1973. Subsequent evolution of individual x-ray structures is demonstrated with high time resolution in Figure 2, using filters 1, 3 and 5 (3 mil Be; 6-13 \AA); the exposure time for each filter in Figure 2 is 1-1/4 sec, with about 9 sec between consecutive images. Figure 3

shows the total x-ray flux recorded by the Be window (2-8 \AA) proportional counter (also part of the S-056 instrument package), the flux observed at a sample frequency (4995 MHz) in the microwave range, and the Sudden Frequency Deviation (SFD) for the event. Both the microwave flux and the SFD (Donnelly, 1974) are shown here because they indicate the presence of high energy, nonthermal electrons and may be associated with the observed soft x-ray brightenings*.

An 88 sec exposure of filter 1 starting at 18:25:38 showed no enhancement, thereby indicating that very little preflare heating occurred in this event. Most of the x-ray flare core was visible in a subsequent 30 sec exposure of filter 2, determining the soft x-ray flare start as about 1827 UT. This start time is verified by the presence of a small x-ray enhancement in the Be counter at 1827 UT, followed by a steeper rise about one minute later.

Examination of Figure 1b, 1c, and Figure 2 shows that the curved x-ray structure comprising the flare core was nonuniform in brightness and, in fact, seemed to consist of several sets of striations essentially perpendicular to the long axis, e.g., see arrows in Figure 1b. Each set of striations was about 4 - 5

* An SFD is a sudden frequency disturbance in which the received frequency of a high frequency radio wave reflected usually from the F-region of the ionosphere suddenly increases, peaks and then decays to the transmitted frequency. In effect, SFD's are high time resolution, broadband (1-1030 \AA), detectors of impulsive ionizing radiation from flares. Donnelly (1969) has shown that the time profile of an SFD is similar to that of impulsive x-rays above 20 keV and therefore, indicative of high energy electrons above that energy range.

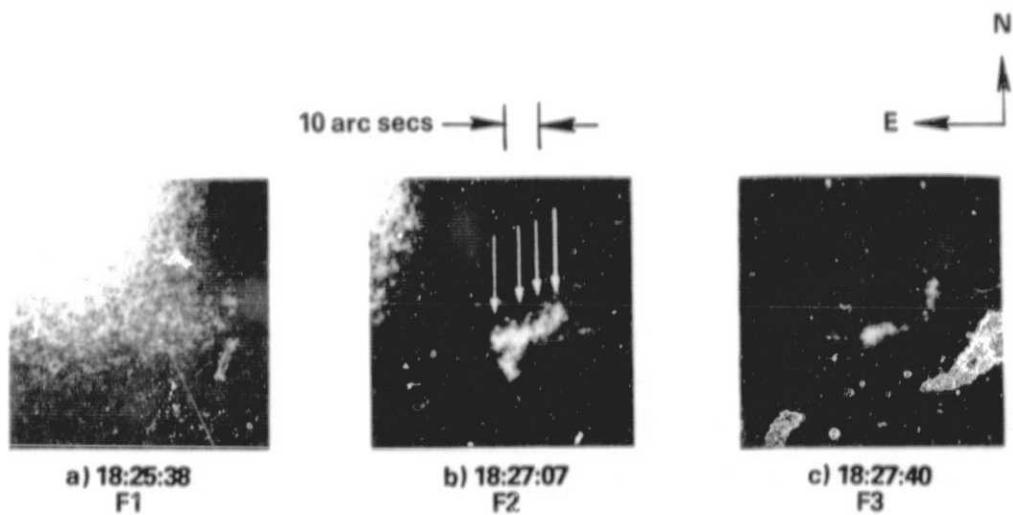
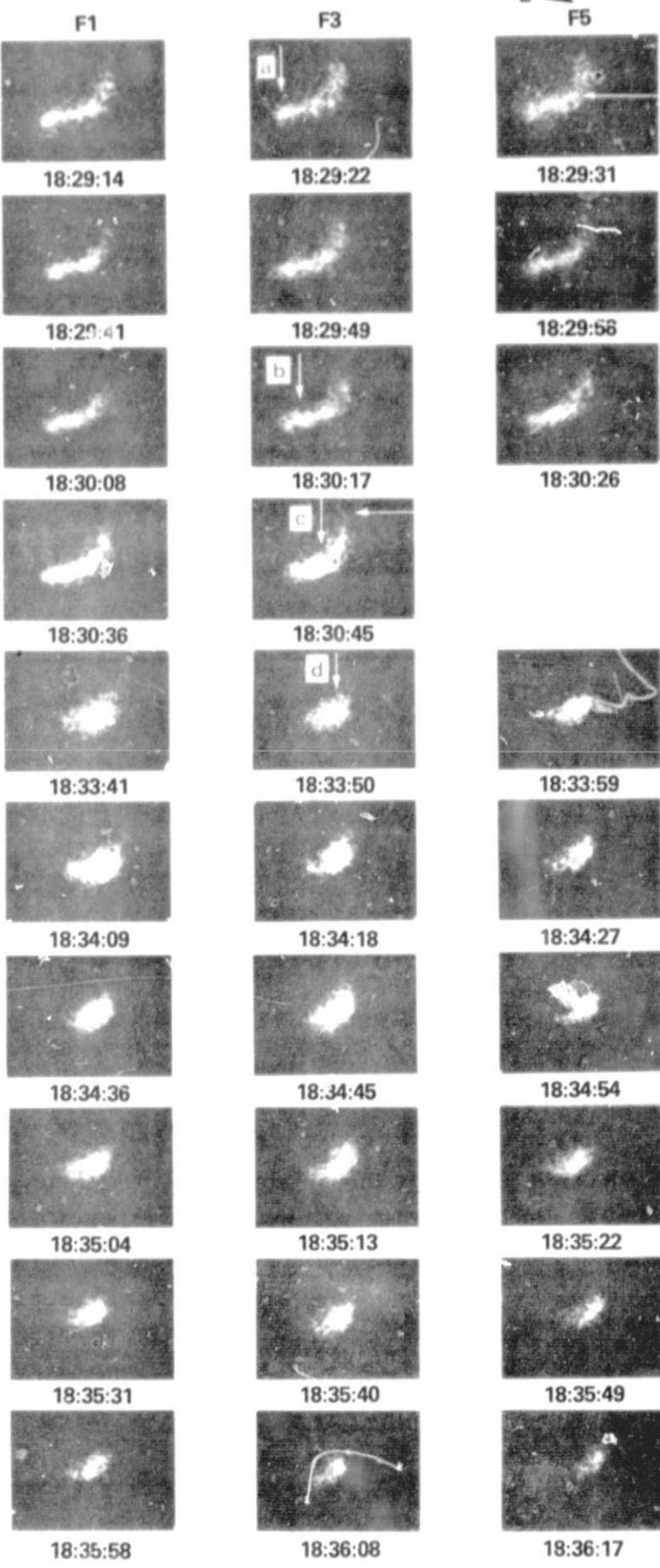


Figure 1 X-ray pictures taken with the S-056 x-ray telescope showing the start of a flare on 5 September 1973. a) 1/2 mil Al (8-16Å); b) 1/4 mil Al (8-22Å); c) 1/10 mil Ti (6-14Å, 27-47Å). The bright feature to the upper left, visible in (a) and partly in (b), shows the x-radiation from another part of the active region. This emission does not appear in subsequent figures because of the shorter exposures. In all cases, the given times correspond to the start of the exposure.

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Figure 2 Subsequent evolution of the 5 September 1973 flare, using filters 1, 3 and 5 (3 mil Be; 6-13Å). The exposure time for each filter is 1-1/4 sec, with about 9 sec between consecutive images. See text for details.

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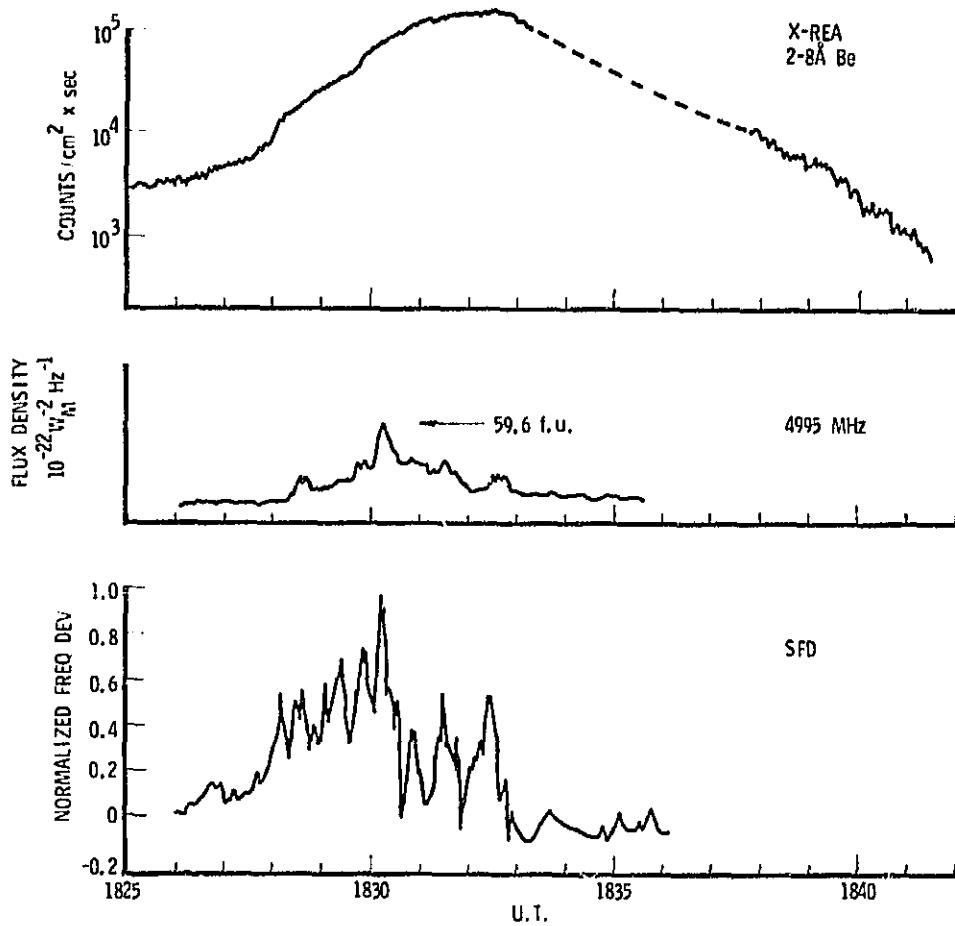


Figure 3 The total x-ray flux recorded by the Be window (2-8Å) proportional counter (also part of the S-056 instrument), the flux observed at a sample frequency in the microwave range, and the Sudden Frequency Deviation (SFD) for the 5 September 1973 flare. The dashed line in the Be counter printout, corresponding to a time during which data were lost because of inadequate ground station coverage, have been sketched from the SOLRAD records. The microwave data came from Sagamore Hill.

arc secs in length. Evidence of short crosswise striations can best be seen in the longer exposures of Figures 1b, 1c, and in some shorter exposures of Figure 2, especially the first three pictures taken with filter 1. Information about individual striations within a set is limited to 1-2 arc secs by the graininess of the SO-212 film used in the experiment. We interpret the crosswise striations perpendicular to the main axis of the flare core as individual loops in a long arcade. This interpretation is also suggested by comparing the x-ray core with magnetic field line calculations, to be discussed later.

Of most importance here is the fact that as the flare evolved, different sets of individual x-ray "striations" brightened consecutively. This suggests that some excitation moved perpendicular to the magnetic field of the arcade, triggering instabilities that may have existed in the preflare structure. The sequential brightening of x-ray features a - d, can best be seen in the filters 3 and 5 sequences of Figure 2 (vertical arrows). For example, at 18:29:22 UT feature a (arrow) at the eastern end of the flare core was brightest. A second x-ray feature b had begun to brighten by the next filter 3 picture, was quite noticeable in the accompanying filter 5 frame, and had become very intense by 18:30:17 UT (arrow). Feature b remained bright through 18:30:45 at which time a third x-ray structure c intensified (vertical arrow).

By 18:33:41, corresponding to a time shortly after flare maximum, the core had changed appreciably in shape. A data gap precluded obtaining details of the change in shape. However, careful comparison of photos taken immediately before and after maximum indicated that the most intense part d of the flare core after 18:33:41 was located about 20 arc secs to the right of the site of the initial flare brightening. Very little motion of the intense source of x-ray emission was observed after 1834 UT.

In two instances, a narrow line of x-ray emission was centrally located along the flare core [see filter 5 at 18:29:31 (arrow) and a fainter line extending almost to the top of the picture taken with filter 3 at 18:30:45 (horizontal arrow)]. Each central line had intensified before the sequential brightening of distinct x-ray features had occurred at that particular position. The timing between these linear x-ray source brightenings suggests that some propagation occurred from left to right early in the rise phase and, further, the position of the linear features near the central part of the core suggests that the propagation may have occurred near the tops of adjacent loops rather than off to one side closer to the footpoints.

All images taken after 1827 UT showed x-ray emission distributed along most of the flare core. This implies that some energy was initially released along most of the arcade near the flare start and continued to be emitted along the entire core throughout the entire event. On the other hand, the source of intense x-radiation evident in filters 3 and 5 was quite localized, implying that the highest temperatures and densities were much more concentrated and occurred progressively along the core as the event evolved. The position of the most intense x-ray feature d, observed after maximum, seems to be along the same line-of-sight as the 16×10^6 K Fe XXIII and Fe XXIV emitting plasma reported by Cheng and Widing (1975).

The fact that different brightenings occurred at soft x-ray wavelengths during the same general time period as the multiple impulsive peaks might suggest that the two phenomena are related. Major SFD spikes took place between 1828 and 1833 UT, with the largest one occurring shortly after 1830 UT. Correspondingly, the different x-ray features brightened successively between 18:29:14 and until some time prior to 18:33:41 with little motion of the intense x-ray source---

and therefore of the implied triggering mechanism --- observed after that time. The 2-8Å proportional counter flux also began to rise significantly above background at 1828 UT, concurrent with the SFD. On the other hand, there does not seem to be a one-to-one relationship between the brightening of a specific x-ray feature, such as a - c, and a distinct 4995 MHz or SFD peak. The SFD profile had much more rapid temporal variations than were suggested by the soft x-ray observations. Consequently, we can only say that although a relationship may exist between the thermal and nonthermal phenomena, the specific connection is certainly not obvious.

Figure 4 shows some magnetic field data for McMath 510 taken near 2015 UT at The Aerospace Corporation's San Fernando Observatory on 5 September. Also indicated are the relative position of the x-ray core and of the most intense features a - d in it. Magnetic data were obtained by averaging two high resolution magnetograms of the same region taken 4 minutes apart, thereby enhancing the signal to noise ratio. For identification purposes, we include (Figure 4a) a magnetogram showing a larger part of McMath 510 with a box delineating the location and relative scale of all remaining pictures in this figure (white = heavy line = follower polarity). The potential field calculations were done using the Schmidt computer program (e.g., Schmidt, 1964, 1965), modified by H. H. Hilton at The Aerospace Corporation.

We tried to determine if any peculiarities in the magnetic field indicated why the x-ray core brightened in segments rather than uniformly. Examination of Figure 4 shows that the x-ray core lay alongside some follower polarity located near the large leader spot. Several other regions of bipolar flux were

also positioned nearby. In fact, the degree to which the x-ray core followed the magnetic contours was in itself striking. The brightest part of the core visible prior to flare maximum lay almost completely within one curve on the magnetogram (to the left of the dashed line dividing the core in Figure 4b), whereas the most intense part evident after 1833 UT was positioned in the second curve (to the right of the dashed line).

Examination of photospheric field strengths and gradients, as well as of the field line calculations, offers some information about the event. The flare's most intense features, b - d, were located near relatively large areas of opposite polarity, in regions with maximum field strengths of about 225 gauss and gradients varying from 0.3 to 0.5 gauss/km. Conversely, the position of x-ray feature a corresponded to a region containing only small areas of mixed polarity. Maximum field strengths of only 125 gauss were observed near a; however, opposite polarities were closely spaced, resulting in gradients of about 0.5 gauss/km.

It is difficult to state whether field gradients of a few tenths of a gauss/km are necessarily indicative of flares. As Rust (1974) points out, reported field values depend heavily on the aperture of the instrument and on the seeing conditions. In the case of the Aerospace Corporation's magnetograph data for 5 September, both seeing and instrument aperture of 0.4 arc secs were such as to produce an excellent magnetograph. In the past, however, the quality of observations has varied appreciably, as suggested by the fact that flare-associated magnetic gradients have ranged from 0.1 gauss/km (Severny, 1969) to 8 gauss/km (Rust, 1974), while gradients of 16 gauss/km (Title and Andeln, 1971) have been

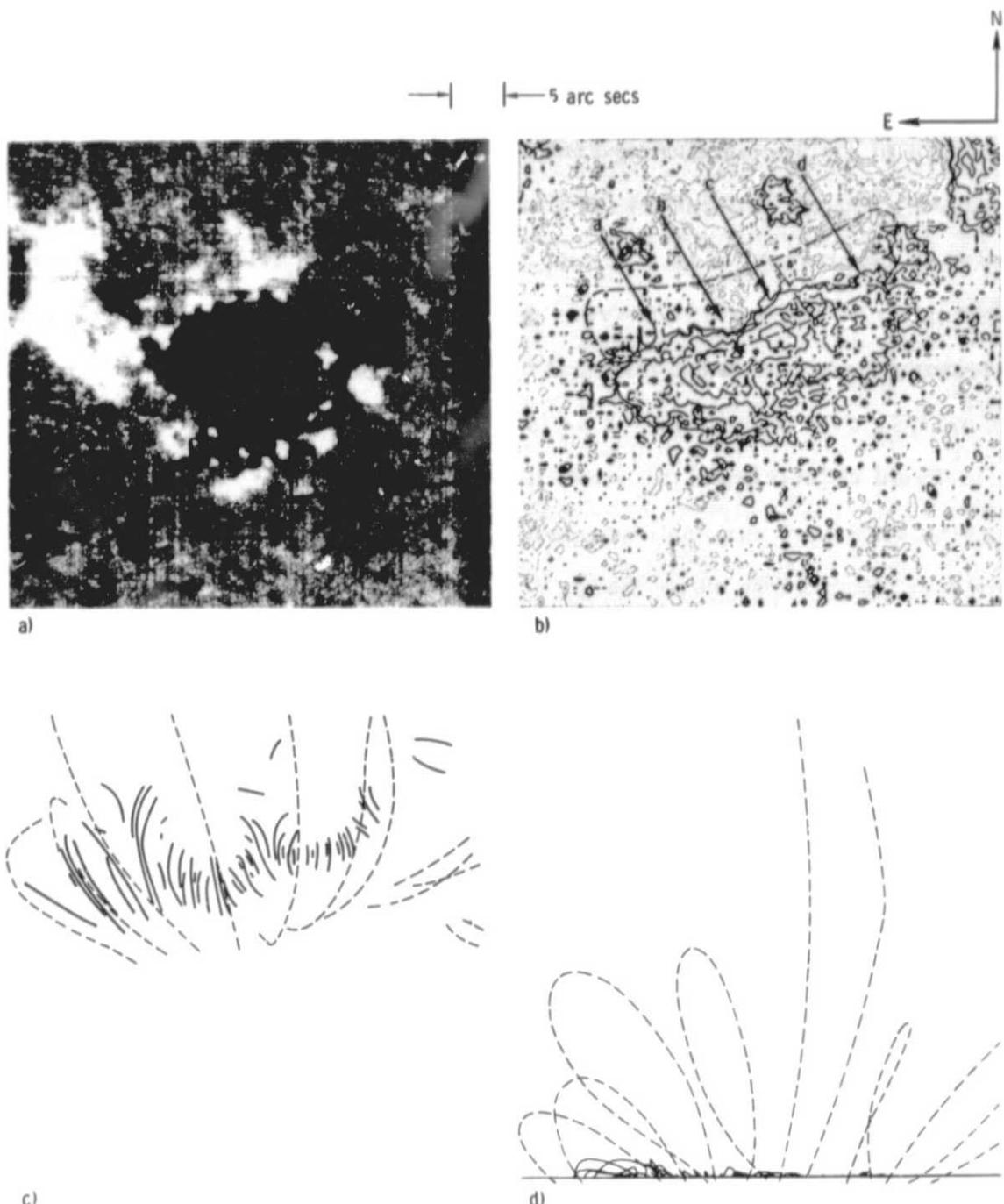


Figure 4 Magnetic field data for McMath 510 taken near 2015 UT at The Aerospace Corporation's San Fernando Observatory on 5 September 1973 by R. G. Teske. The relative position of the x-ray core and of the most intense features a - d are indicated. (4a) shows a larger part of McMath 510, with a box delineating the location and relative scale of all remaining pictures in the figure (white = heavy line = follower polarity). The 5 arc sec scale refers only to 4b - d.

reported in stable, nonflaring spots. It would be better to determine the gradient's change throughout the flare. It is not possible to make this observation in the present case since no high resolution magnetograms were taken prior to the event; however, magnetograms from Kitt Peak National Observatory did show that significant changes occurred in the reverse polarity inclusions, over a time period on the order of days from 2-6 September.

Field calculations, as viewed from above (4c) and from the side (4d) show an arcade of varying diameter positioned along the locus of follower polarity. Footpoints were chosen at equally spaced intervals along the polarity inclusion, as well as at other sites coincident with, or near, the x-ray core. Magnetic lines of force with one foot positioned near the edge of the follower polarity inclusion turned out to be quite short, i. e., about 5 arc secs in length, in good agreement with the coincident x-ray core. On the other hand, footpoints located more towards the center of the inclusion were much longer, higher and not coincident with any x-ray structures.

Examination of Figure 4 shows that the brightest x-ray features, b - d, were located at places where the magnetic energy density was the highest.

4. SUMMARY AND CONCLUSIONS

Analysis of the soft x-ray data leads to the following conclusions:

- 1) The close similarity between calculated magnetic fields lines and the overall structure of the x-ray core strongly suggests that the flare occurred in an entire arcade of loops rather than in a single loop.

2) The sequential brightening of different x-ray features suggests that some triggering disturbance moved from one side to the other in the flare core, with the transmission probably located near the top of closely spaced arches in the arcade. We can calculate a propagation velocity by determining the time and distance between pairs of brightening x-ray structures. In particular, features a and b, as well as features b and c, were separated by 5300 km. The time between maximum brightness of successive features was between 19-28 sec where the range is primarily the result of the 9 sec time between exposures. A propagation velocity between 180-280 km/sec is implied. Due to the gap in observations, the time of maximum intensity for feature d is not known; consequently, the corresponding propagation velocity cannot be calculated.

The possibility of simple particle drifts across field lines due to $\vec{E} \times \vec{B}$ and $\vec{v} \vec{B}$ forces can immediately be excluded as an explanation for the sequential brightening since these types of drift velocities are typically less than a cm/sec for the solar corona. One phenomenon that could explain the sequential x-ray brightening is a magnetosonic wave, since the latter can travel perpendicular to the magnetic field direction. We can find the velocity of a magnetosonic wave (Spitzer, 1967) from

$$v^2 = \frac{v_A^2 + v_S^2}{1 + v_A^2/c^2} = v_A^2 + v_S^2 \text{ for } v_A \ll c$$

where v_A = Alven speed and v_S = sound speed. The Alven speed $v_A = 2.20 \times 10^{11} B/\sqrt{n}$ cm/sec and c is the speed of light.

The value for the magnetic field in the region of the x-ray core was obtained in the following way. We assumed the field lines were roughly half of a semicircle so that the height at the top of the x-ray loops was estimated to be ≈ 1800 km, i.e., half the length of the x-ray striations. Then the field strength at a height of 1800 km was calculated by using potential field approximations and the photospheric field values obtained from the magnetogram. The values for $|\vec{B}|$ at the 1800 km height were typically 80 gauss at positions corresponding to x-ray features b - d, but were only 50 gauss near x-ray structure a. Then using an electron flare density $n = 2 \times 10^{11} / \text{cm}^3$ (similar to the Fe XXIII-XXIV emitting plasma for this flare, Cheng and Widing, 1975), the Alfvén velocity ranges between 246-393 km.

$$\text{Correspondingly, the sound speed, } v_s^2 = \frac{\gamma_e k T_e + \gamma_i k T_i}{m_i + m_e}$$

If we can assume that $T_e = T_i = T$, $m_i + m_e \approx m_i$ and that $\gamma_i = \gamma_e = \frac{2+m}{m} = 2$ with the number of degrees of freedom, $m = 2$ for a two-dimensional compression wave, where no collisions are assumed among the thermal particles during passage of the wave. The expression for the sound speed then becomes

$$v_s = 2\sqrt{kT/m_i} = 1.8 \times 10^7 \sqrt{T_6} \text{ cm/sec}$$

where T_6 is in millions of degrees Kelvin. It is not clear what temperature should be used in the sound speed equation. Presumably the flare region is not isothermal so that the magnetosonic wave passes through a wide range of temperatures in propagating down the arcade. If we use a representative temperature of 1.5×10^6 K, v_s turns out to be 220 km/s.

Using these values for V_A and V_S , the velocity of the magnetosonic wave then ranges between 330 and 450 km/sec. This speed is roughly a factor of two higher than that indicated by the sequentially brightening x-ray features. However the fact that the observed speed is less than the calculated speed is not surprising since the need to set off local instabilities surely acts like a modification of the equation of state that determines the signal velocity, and presumably slows it down.

Furthermore, it is difficult to know exactly what values to use in the calculation of the sound and Alfvén speeds. If the wave propagated at a lower height in the atmosphere, the contribution from the sound speed would be much smaller due to the decreased temperature. Correspondingly, the Alfvén speed for a wave propagating at a lower altitude would also be smaller if the ratio of B/\sqrt{n} decreased.

3) We were able to determine the location of the initial energy release and its magnetic field characteristics. The site of the initial x-ray brightening was characterized by (calculated) magnetic fields that were long and high, with a few low lying field lines due to the presence of some closely-spaced bipolar regions. The two most intense x-ray features appeared later in the flare and were located in places where the magnetic field composing the arcade had a small radius of curvature with horizontal field gradients higher than the surrounding region, and where the axis of the arcade changed direction.

4) Some energy deposition and heating took place along most of the arcade near the flare start. However, the high temperature and density regions were visible a few minutes later in the event and were much more concentrated, occurring at different positions along the flare core as described in #2 and #3 above. We feel that the geometry of the arcade strongly influenced the propagation of the triggering disturbance, as well as the storage and site of the subsequent deposition of energy.

5) Since sequential soft x-ray brightenings occurred during the same general time period as multiple high frequency microwave and SFD peaks, some relationship may exist in this case between thermal and nonthermal components; however, the specific connection is not obvious.

There are still remaining questions concerning the source of the energy. Presumably the disturbance propagating down the arcade triggered a metastable state, i.e., one which was stable against small amplitude perturbations but not against larger ones. It is difficult to understand how sufficient energy can be stored in fields with intensities suggested by the photospheric measurements. As Piddington (1974) has suggested, however, each flux tube probably consists of twisted strands containing magnetic energy that can be released under the correct conditions, whereas a potential field is already in the lowest energy state and has no free energy. (We have used a potential field approximation here to give an idea of the gross magnetic configuration, simply because very little is known about the direction or magnitude of currents in the solar atmosphere. Furthermore for low-lying field lines, there is very little difference in the field topology resulting from potential or from force-free field considerations.)

What are the "correct conditions" for the energy to be released? One possibility arises due to resistive instabilities stemming from a long-wavelength "tearing" mode, corresponding to breakup of a current layer along current-flow lines. Typically one thinks of the tearing mode in terms of a sheet pinch where the magnetic field changes sign, however it is not essential that the magnetic field be 0, but rather that $\vec{k} \cdot \vec{B} = 0$ (Furth, et al., 1963),

where \mathbf{k} is the wave vector of the disturbance. Furth et al. note that for any magnetic field with finite shear, \vec{k} may be chosen so that $\vec{k} \cdot \vec{B} = 0$ at one or more points. In order to invoke the tearing mode instability then, it is only necessary to note that an arcade-- such as that observed on 5 September -- with loops of varying diameter or, correspondingly, with varying field strengths along its length, actually consisted of a sheared magnetic field. The magneto-sonic wave would serve to "trigger" energy releases as it propagated down the arcade by steepening the gradients, thereby making it easier for the tearing mode to occur.

The 5 September arcade could have consisted of twisted flux tubes which became kink unstable and evolved into helical flux tubes, where the azimuthal fields of neighboring kinks formed extended X-type neutral lines (Kuperus and Rosenberg, 1975). The sequential x-ray brightening would then be consistent with a domino effect resulting from adjacent pairs of flux tubes successively going unstable, with the intense x-ray features occurring where the magnetic energy density was highest. If each strand in the arcade were twisted, sufficient energy (Piddington, 1974) could have been stored to explain an event having soft x-rays, type II and III bursts, as well as other nonthermal manifestations such as high frequency microwave flux and an SFD. This event demonstrates that all energy emitted during a flare need not be released immediately nor in the same location, thereby eliminating some problems encountered in most flare theories.

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